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50 Gbps data transmission through amorphous silicon interlayer grating couplers with metal mirrors

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The fabrication of highly efficient interlayer grating couplers for multilayered a-Si:H waveguides by introducing two metal mirrors to reflect back the diffracted light was demonstrated. The coupling efficiency from one layer to the next was 83% (loss of 0.8 dB). The 50 Gbps signals were successfully transmitted from one layer to the next without any eye degradation.

The introduction of photonics into LSI chips is expected to be a key technology for the development of high-performance and energy-efficient computing systems.[1–3] Hydrogenated amorphous silicon (a-Si:H) is a promising core material for photonic waveguides because it can be deposited at a process temperature of ~300 °C, which satisfies the temperature limitations of the CMOS backend process.[4–6] In addition, multistacking of optical layers can be realized by alternately depositing a-Si:H and SiO_2.[7,8] Furthermore, optical interconnects using a-Si:H in a three-dimensional (3D) structure can provide a higher density, resulting in a higher total data capacity, than conventional, single-layered crystalline-silicon optical circuits. Recently, several researchers have successfully achieved low-loss a-Si:H waveguides deposited by plasma-enhanced chemical vapor deposition (PECVD).[9,10]

To realize multistacked layers of 3D optical interconnects, vertical coupling between the layers is necessary. A vertical-type directional coupler using evanescent coupling was reported with a coupling distance of ~200 nm.[11,12] On the other hand, grating couplers can achieve vertical coupling between layers with a much larger separation distance.[13–15] We initially proposed the use of a pair of grating couplers to achieve the interlayer coupling, and we obtained a coupling efficiency of 22%.[16] These grating-type couplers were also reported for fabricating chip-to-chip connections.[17,18] In a recent study, we have theoretically shown an improved coupling efficiency of 90% realized by introducing a pair of metal mirrors to the interlayer grating couplers with a layer distance of 1 µm.[19] In this paper, we report interlayer grating couplers with a coupling efficiency higher than 80% and a wide-band signal transmission capability up to 50 Gbps.

Figure 1 shows a schematic illustration of the interlayer grating couplers. The device design was based on the simulation results in Ref. 19. In this work, the interlayer grating couplers were sandwiched by Au mirrors to improve the coupling efficiency. The light diffracted from the gratings to the opposite side would be reflected back to the grating coupler by the mirrors. Therefore, the distance between the metal mirror and the gratings D_M should satisfy phase matching conditions. The peak coupling efficiency can be obtained when the optical path length difference between the light diffracted upward from the gratings and the light reflected by the metal mirror is equal to the integral multiple of the wavelength. The peak wavelength can also vary with D_M owing to the phase matching condition as well as grating depth. Thus, the coupling efficiency varies periodically with D_M (in the case of a fixed wavelength) as shown in Fig. 2, which was obtained from 3D finite-difference time-domain (FDTD) simulations at a wavelength of 1.55 µm. From this simulation, the maximum coupling efficiency was 90% with D_M of 800 nm.

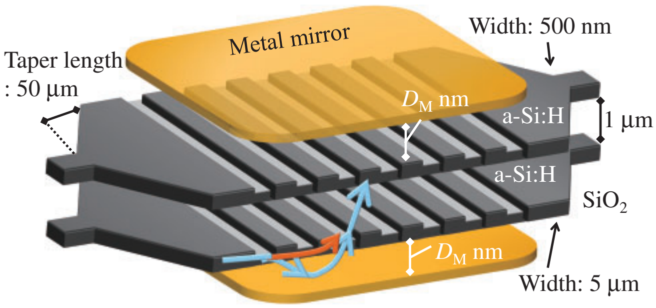


Fig. 1. Device structure of interlayer grating couplers with metal mirrors.

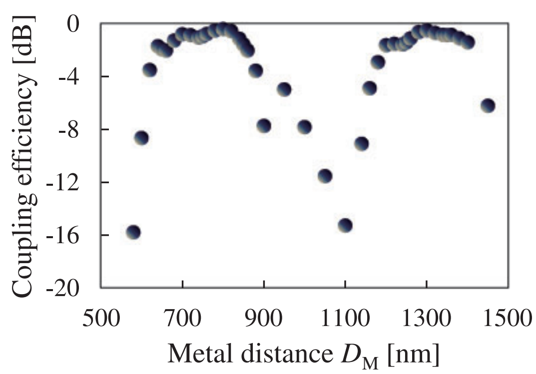
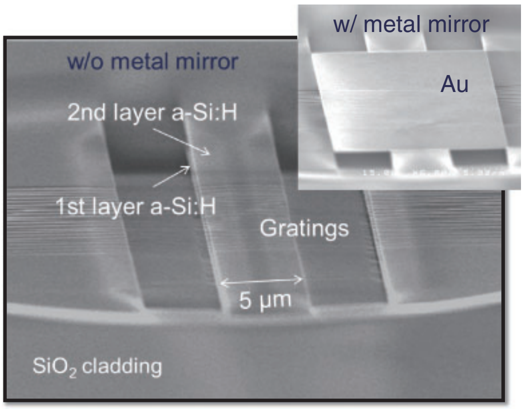


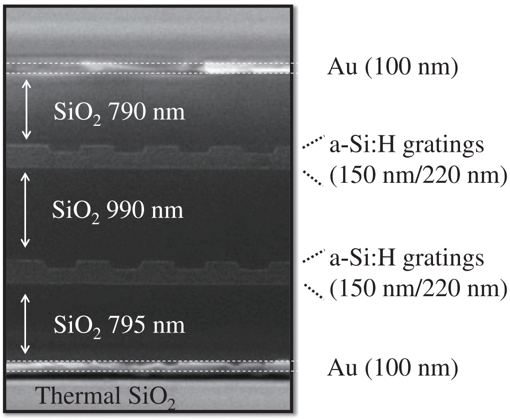
Fig. 2. Simulated coupling efficiency of interlayer grating couplers as a function of distance between the metal mirror and the gratings D_M.

The interlayer grating couplers with metal mirrors were fabricated on a Si substrate with a 3-µm-thick thermal SiO_2 layer. For the metal mirrors, a 100-nm-thick Au film was evaporated on the surface of the SiO_2 followed by a lift-off process. D_M was controlled by the deposition of SiO_2 and a chemical mechanical polishing (CMP) process. For each process step, the layer thickness was checked using a thickness monitor without breaking the wafer.

Two grating couplers were placed parallel to each other with a layer distance of 1 µm (distance can be increased as needed). The layer distance was controlled by a layer of SiO_2



(a)



(b)

Fig. 3. (a) Bird's-eye-view and (b) cross-sectional SEM images of the fabricated interlayer grating couplers.

as done for D_M. On the surface of the SiO_2, a 220-nm-thick a-Si:H film for each layer was deposited by PECVD under the following conditions: 100 sccm SiH_4 flow rate, 100 sccm Ar flow rate, 100 W power, and 300 °C deposition temperature.

The input and output ports were 500-nm-wide wire waveguides. Through 50-µm-long tapered structure sections at the grating region, the waveguides were expanded to 5 µm. The total device length of the grating coupler was 150 µm including the 5-µm-wide and 50-µm-long waveguides and gratings. The waveguide patterning was carried out by electron-beam (EB) lithography, and an inductively coupled-plasma reactive-ion-etching system was used for etching the waveguides and gratings. The etch depth of the gratings was 70 nm. In the coupling region, the grating period was 640 nm (power leakage factor: 1700 cm^{-1}) for 20 pairs of uniform gratings (duty cycle: 50% in physical length).

Bird's-eye-view and cross-sectional scanning electron microscopy (SEM) images of the fabricated interlayer grating couplers are shown in Fig. 3. In Fig. 3(a), the gratings are shown with (inset) and without the top metal mirror. The SiO_2 layer was removed to obtain a clear SEM image. From the cross-sectional SEM image in Fig. 3(b), the thicknesses of the top and bottom D_M were 790 and 795 nm, respectively, compared with the target D_M of 800 nm. The layer distance was 990 nm, which means that the a-Si:H, SiO_2, and Au layers were stacked with a thickness accuracy of approximately 10 nm. We performed an additional simulation of the interlayer grating coupler under the conditions of the

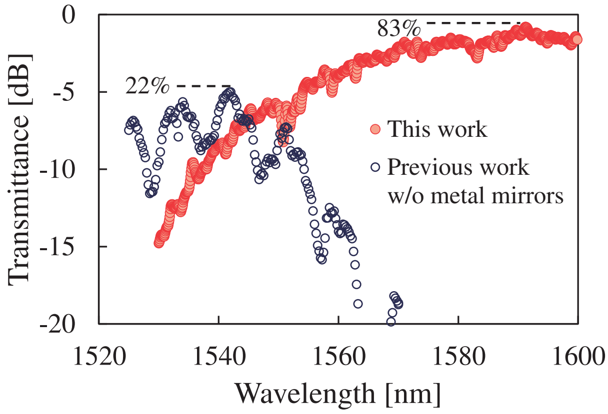


Fig. 4. Measured wavelength dependence of coupling efficiency of interlayer grating couplers. In this work (red circles), D_M was 800 nm, and the grating had a 640 nm period with 20 grating pairs. The results from the previous work[16] without metal mirrors are shown in open blue circles, and the grating had a 640 nm period with 10 grating pairs. Note that the previous work involved fully etched gratings.

actual fabricated structure and estimated the peak coupling efficiency to be 88%.

Please note that all of the processes (a-Si:H, SiO_2 deposition, and CMP processes) are comparable to the CMOS process. Although we used Au for mirrors owing to equipment limitations, the material for the mirrors can be replaced by Al, which is used in CMOS contacts.

Next, coupling efficiency measurements of the fabricated couplers were carried out using transverse-electric (TE) polarized light from an amplified spontaneous emission (ASE) source. The light was coupled to the wire waveguides with inverted-taper spot-size converters through tip-lensed single-mode-fibers.[20] Figure 4 shows the coupling efficiency of the interlayer grating couplers including the mode conversion loss of the two tapered sections between the wire and wide-width waveguides. The peak coupling efficiency was improved to 83% (−0.8 dB) compared with that in a previous work without metal mirrors (22%).[16] The 3 dB bandwidth was more than 40 nm, which was limited by the output wavelength range of the light source.

We also investigated the high-speed data transmission performance of the interlayer grating couplers. Optical signals modulated with 2^{-7} pseudorandom binary sequence (PRBS) patterns were used as input for the couplers. The measured wavelength was set at 1560 nm owing to the operating limits of our erbium-doped fiber amplifier. The eye diagrams with the device under test (DUT) and without the DUT, which means only fiber-to-fiber (F-to-F) as a reference, at data rates of 40 and 50 Gbps are shown in Figs. 5(a)–5(d). Clear eye openings were observed with our device compared with those of the F-to-F, even at a data rate of 50 Gbps. The jitter RMS values of the F-to-F and DUT configurations were 1.63 ps [Fig. 5(a)] and 1.41 ps [Fig. 5(b)] for 40 Gbps, and 1.31 ps [Fig. 5(c)] and 1.42 ps [Fig. 5(d)] for 50 Gbps, respectively. There was no noticeable difference in jitter value among data speeds. These experiments proved that multiple reflections by the mirrors above and below the couplers did not cause any degradation of the signal transmission.

In summary, we demonstrated the fabrication of highly efficient interlayer grating couplers with metal mirrors. The

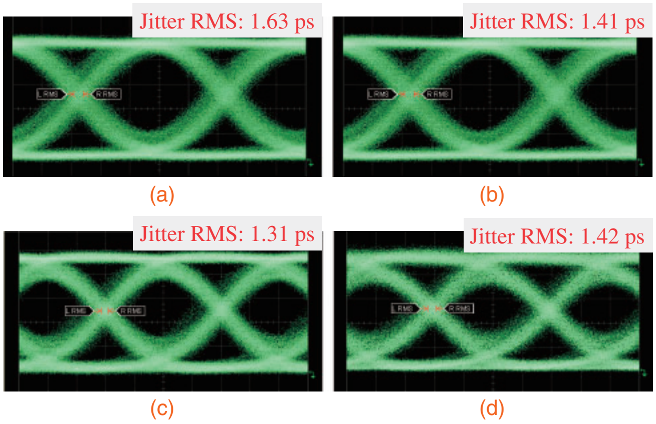


Fig. 5. Measured eye patterns for 40 Gbps: (a) F-to-F and (b) DUT. Measured eye patterns for 50 Gbps: (c) F-to-F and (d) DUT.

core material for the waveguides was a-Si:H and all of the fabrication processes were carried out below 300 °C for CMOS backend-process compatibility. The measured peak coupling efficiency was more than 80%, and clear eye openings were observed at data rates up to 50 Gbps.

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